AN EVALUATION OF BRAKING PERFORMANCE AND COMPATIBILITY OF TRACTORS AND TRAILERS WITH DISC AND DRUM BRAKES

Test Conducted For Volvo Trucks North America

Test Number: RAI-VOL-55

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INTRODUCTION

At the request of Volvo Trucks North America, Radlinski & Associates, Inc. (RAI) conducted a test program to evaluate braking performance and compatibility of tractors and trailers with disc and drum brakes. Test vehicles utilized consisted of three different Volvo VN 6x4 tractors with disc and drum brakes and a single 53-foot, tandem-axle Great Dane semi-trailer. This semi-trailer was set up so that the tandem-axle "slider" assembly could be quickly changed from one equipped with disc brakes to another one equipped with drum brakes. The disc brake tractor was equipped with an electronically controlled braking system (ECBS). The drum brake tractors (two different ones were actually used) and the trailer with both disc and drum braked sliders utilized conventional, pneumatically controlled braking systems (PCBS) with ABS.

The tractors were tested with an un-braked FMVSS 121 control trailer loaded to achieve GVWR on the tractor and in combination with the Great Dane semi-trailer in several different loading configurations ranging from empty to loaded to a GCW of 80,000 lbs. The Great Dane semi-trailer was also tested with a un-braked lightweight 4x2 tractor to characterize the braking performance of both disc and drum brake sliders at low braking pressures, typical of actual on-road use.

The primary purpose of the testing was to compare disc and drum brake performance and to assess the compatibility of tractors and trailers equipped with both types of brakes. In addition, the program included limited testing to assess the braking performance of both disc and drum brake tractors that had accumulated significant mileage in the US Xpress fleet.

TEST VEHICLES

Test vehicles included the following units:

- 6x4 Volvo VN tractor with drum brakes - Supplied by US Xpress for testing with used ("as-received") brakes.
- 6x4 Volvo VN tractor with disc brakes and ECBS - Supplied by US Xpress for testing with used ("as-received") brakes and also with new pads and rotors.
- 6x4 Volvo VN tractor with drum brakes supplied by Volvo North America for the testing with new linings and drums
- Tandem-axle 53-foot Great Dane semi-trailer with disc brake and drum brake sliders (only tested with new brake components).

Specifications and more detailed information on the test vehicles are provided in Appendix A. Three different brake manufacturers were represented among the test vehicles. ArvinMeritor drum brakes (15 x 5 front/16.5 x 8 rear) and ArvinMeritor disc brakes (Duco C) were used on the tractors. Hendrickson drum brakes (16.5 x 8.625) were used on one trailer slider and Knorr-Bremse disc brakes (SB-7) were used on the other trailer slider.

In addition to these test vehicles, two other vehicles were utilized during the testing. A standard FMVSS 121 control trailer was used for tractor brake burnishing and other portions of the tractor brake testing. A lightweight 4x2 tractor was used for trailer brake burnishing and those tests where the trailer brakes only were being evaluated (i.e. trailer brake characterization tests).

Photographs of the test vehicles are shown in Figures 1 through 3. Figure 1 shows one of the tractors (all three tractors looked essentially the same) with the FMVSS 121 Control Trailer. This trailer was used with the tractors for burnishing, stopping distance, and parking brake portions of the testing. The FMVSS 121 Control Trailer is a single-axle semi-trailer that does not have any brakes. Its primary purpose is a to load the tractor to GVWR and all of its ballast is placed directly above the kingpin so that only the tractor load is increased as ballast is added. The Control Trailer axle load is essentially fixed at 4,500 lbs per FMVSS 121.

Figure 2 is a photograph of the Great Dane test trailer with the lightweight 4x2 towing tractor used to burnish the trailer with the drum brake and disc brake sliders and to characterize these two different trailer brake systems. The semi-trailer was loaded with concrete blocks placed above the trailer axles. While the goal of the loading was to have the total combined weight (GCW) as close as possible to the GAWR of the trailer tandem and to then use the trailer brakes only, to decelerate the load that they were designed to handle, such a loading did not place enough weight over the trailer axle to prevent the trailer ABS from cycling at the brake pressures reached during the burnish. This is despite the fact that a relatively lightweight tractor (bobtail weight = 11,800 lb) was utilized as the towing vehicle. Sufficient weight had to be added above the trailer axle to prevent wheel lockup and this produced a total combination vehicle weight greater than the trailer tandem's GAWR.

In order to account for this higher loading on the trailer brakes, the burnish deceleration and speed change were reduced in accordance with the equations given in SAE J1729, *Parking Brake Drawbar Pull Test Procedure*, which are based on the basic principles of dynamics. By using this approach, the brakes are subjected to the same force level and energy input that they would experience if they were braking a load equal to the GAWR. This results in brake pressures and temperatures equivalent to those that would have occurred had the trailer brakes been operating at the standard burnish conditions and braking a load equal to the GAWR. These would also be the temperatures and pressures that would exist in the trailer brakes if the trailer was fully loaded to GVWR and was mated to tractor with operational brakes that were properly balanced with those on the trailer. By burnishing with the trailer brakes only and using the above loading approach, the influence of variability in the tractor's brakes was eliminated.

The 4x2 tractor was also used during the trailer brake characterization testing but in this case, the brake application pressures (20 and 30 psi), which were selected to represent typical stopping conditions, were lower than those in the burnish and the loading on the trailer axle could be reduced so that the total combination weight was very close to the trailer tandem's GAWR (40,000 lbs).

Figure 3 shows one of the test tractors in combination with the Great Dane test trailer. This is the configuration used for stopping distance, compatibility and fade testing and is the one that best represents how the vehicles are actually used in revenue service. The semi-trailer was loaded with concrete blocks to achieve the desired loading and sand bags were used to trim the test weights. Three different trailer loadings were used: 1) fully loaded, 2) trailer front-end only loaded and 3) empty.

Figure 1 – 6x4 Tractor with FMVSS 121 Control Trailer

Figure 2 – Tandem Axle Semi-Trailer with Lightweight Towing Tractor

Figure 3 – 6x4 Test Tractor and Tandem Axle Semi-Trailer

Table 1 shows the axle weights and total weights for each of the various testing situations.

Table 1 – Nominal Axle Weights for Various Test Conditions

Condition	Weight, lbs.			
	Steer	Drive	Trailer	Total
Tractor Testing With FMVSS 121 Control Trailer	12,350	38,000	4,500	54,850
Trailer Brake Characterization Testing (with lightweight tractor)	7,800	9,200	23,150	40,150
Combination Vehicle testing – fully loaded trailer	12,000	34,000	34,000	80,000
Combination Vehicle testing – trailer front-end loaded	12,000	33,500	12,500	57,500
Combination Vehicle testing – empty trailer	11,500	14,000	10,500	36,000

TEST FACILITY

All testing was conducted by RAI personnel using RAI's facilities and those of the Transportation Research Center (TRC) in East Liberty, Ohio. Burnishing and compatibility testing were performed on TRC's 7.5-mile High Speed Track and stopping distance tests were run on the concrete Skid Pad (dry). Pneumatic testing, roller brake testing and parking brake drawbar testing were performed in RAI's facilities.

INSTRUMENTATION

Test vehicles were equipped with digital data acquisition systems and instrumentation to measure and record vehicle speed, stopping distance, deceleration, brake pressures, brake temperatures and wheel speeds. Speed and stopping distance were determined with a fifth wheel system. Deceleration was measured with an accelerometer. Brake pressures were measured with pressure transducers located in the control line and brake chambers so as to monitor the pneumatic circuits. Thermocouples were installed in the primary shoe of each brake shoe and the inner pad to monitor brake lining temperatures.

The fifth wheel was calibrated prior to testing by driving over a 500 ft measured course to check distance and tire pressure was adjusted as necessary so that the measured distance was within ±2 ft (0.4 percent). The pressure transducers were calibrated against a master transducer. The decelerometer was calibrated by tipping it to the vertical (1 g) position.

In the drag tests, the tractor-trailer combination being tested was towed with another vehicle using a drawbar instrumented with a load cell. The load cell was connected to the data acquisition system in the test combination and a readout was provided to the driver to enable him to modulate the braking to achieve a specific force level.

In addition to the road testing and parking brake tests, static tests were run in accordance with FMVSS/CMVSS 121 to evaluate pneumatic timing (apply and release) of the service brakes. The tests were run with the tractor and trailer in combination, which is a variation from the standard, where the power unit and trailer are tested separately. An accelerometer was utilized to sense first movement of the brake pedal. The accelerometer and pressure sensors were connected to a digital data acquisition that sampled at 200 Hz. Just prior to testing, the pressure sensors were calibrated with a master transducer.

TEST PROCEDURE

Table 2 shows a summary of the test procedure. More detail on the test procedure is provided in Appendix B.

Table 2 – Test Procedure Summary

1. Conduct 60 and 75 mph stopping distance tests and roller brake tests on disc and drum brake tractors with in-use braking systems (>300k miles) utilizing FMVSS 121 Control Trailer.
2. Burnish disc and drum brake tractors after installing new OE materials.
3. Burnish disc and drum brake trailer sliders (brake components were new to start)
4. Conduct 60 and 75 mph stopping distance tests and roller brake tests on disc and drum brake tractors using FMVSS 121 Control Trailer.
5. Conduct parking brake drawbar force tests on disc and drum brake tractors.
6. Characterize low-pressure braking of trailer with disc and drum brake sliders. Run stops from 30 and 60 mph at 20 and 30 psi application pressures; also run roller brake tests.
7. Conduct combination vehicle tests with each of the four possible combinations (drum/drum, drum /disc, disc/drum and disc/disc) loaded to 80,000 lbs.
    a. Pneumatic timing (apply and release)
    b. Roller brake tests
    c. Stopping distance
        i. 60 and 75 mph – full system
        ii. 75 mph – failed tractor primary reservoir
        iii. 75 mph – failed tractor secondary reservoir
        iv. 75 mph – failed trailer control line
8. Conduct compatibility tests on the four different combinations, each at three different trailer loadings (fully loaded, loaded at front only and empty).
    a. Pressure balance
    b. Brake force balance (roller brake tester)
    c. Snub test – 60 snubs, 35 to 20 mph at 6 ft/sec^2, 0.2mile intervals
    d. Drag test – 3000 lbs drawbar force for 5 miles at 30 mph.

The burnish, stopping distance and parking brake tests were performed in accordance with the FMVSS 121 procedure. The roller brake tests were performed with brake temperatures between 150 and 200°F (same brake temperature as stops). In the snub and drag tests, the test were terminated if the brakes became very hot (650°F for drum brakes and 800°F for the disc brakes).

TEST RESULTS

Detailed test data are included in the appendices, which are arranged in the following fashion (Appendix A contains vehicle information and Appendix B includes the detailed test sequence):

- Appendix C – 6x4 drum tractor "as-received" stopping distance results
- Appendix D – 6x4 disc tractor "as-received" stopping distance results
- Appendix E – 6x4 drum tractor with new brakes stopping distance/parking results
- Appendix F – 6x4 disc tractor with new lining stopping distance/parking results

- Appendix G – Characterization of drum brake trailer
- Appendix H – Characterization of disc brake trailer
- Appendix I – Tractor /Trailer stopping distance results
- Appendix J –Tractor/Trailer timing, balance and fade test results

A summary of the data and a discussion of the significant findings are presented in the sections that follow.

<u>Stopping Distance with "As-Received" Brakes and the FMVSS 121 Control Trailer</u>

Figure 4 shows the "as received" stopping distance from 60mph on dry concrete with a full brake application for the drum brake tractor and the disc brake tractor loaded to GVWR using an un-braked FMVSS 121 Control Trailer. Both tractors had been operating in the US Xpress fleet with these braking components for over 300,000 miles (319,000 for the drum brake vehicle and 362,000 for the disc brake vehicle). The FMVSS 121 requirement is 355 feet for loaded tractors. Both the drum brake tractor and the disc brake tractor met the requirement for each of the three stops that were run on each vehicle.

Note that the first 60 mph stops for both the drum and disc tractors were nearly identical. Both units improved in stopping distance with the next two stops. The average stopping distance for the three stops show that the disc brake tractor (which also has ECBS) stops 21 feet or approximately 7.2 percent shorter than the drum brake tractor.

Figure 5 is similar to Figure 4, except that the initial target speed was 75 mph in this case. These stops show that the disc brake tractor stops 33.0 percent shorter than the drum brake tractor based on the average of all three stops for each vehicle.

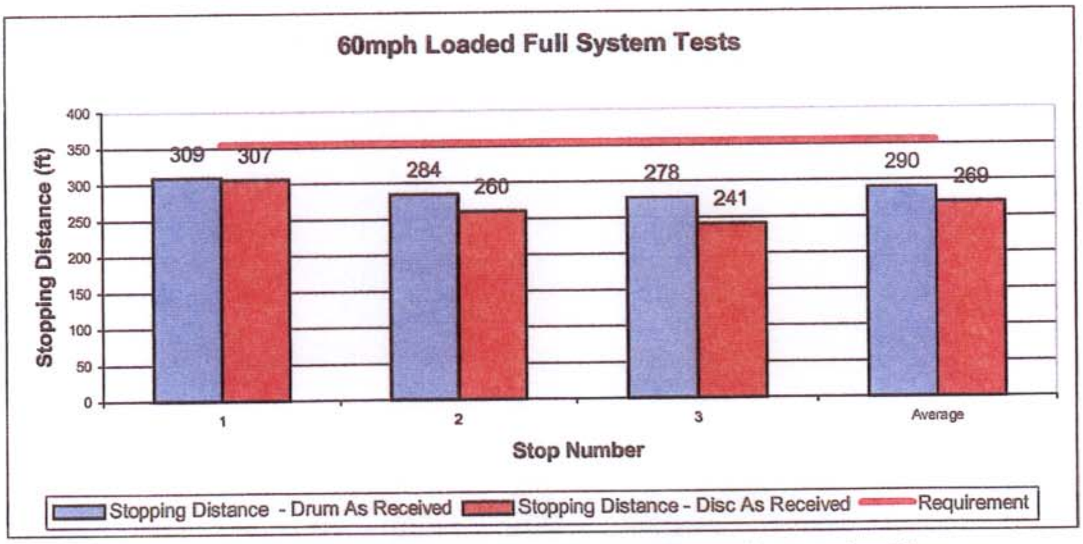


Figure 4 – Summary Results – 60mph Stops "as-received"

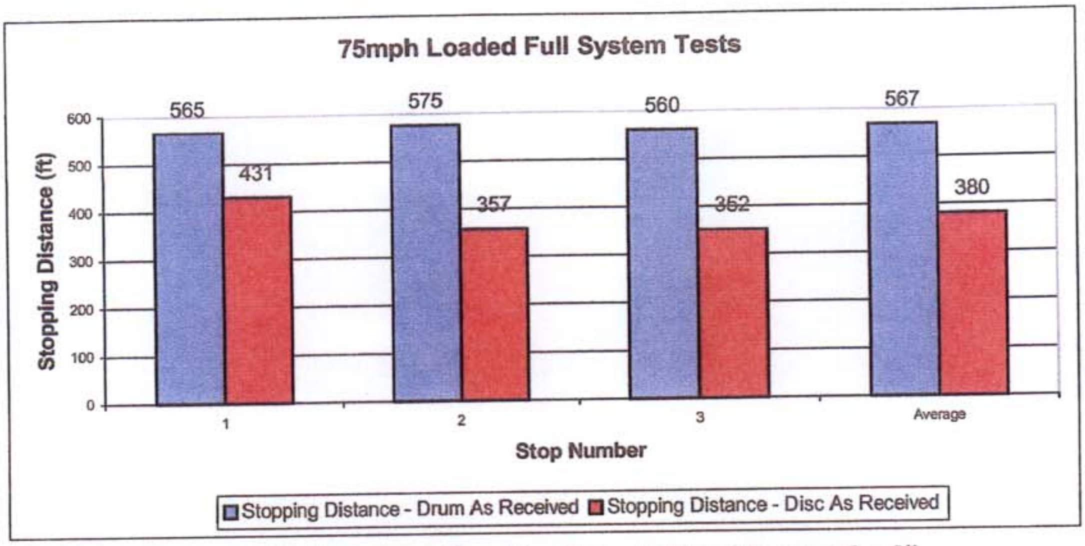


Figure 5 – Summary Results – 75mph Stops "as-received"

Stopping Distance with New, Burnished Brakes and the FMVSS 121 Control Trailer

The braking system on the disc brake tractor borrowed from the US Xpress fleet for "as-received" testing was rebuilt with new discs and pads and new tires were installed. Brakes were then burnished using the Control Trailer and the FMVSS 121 procedure. Since Volvo already had a drum brake VN tractor available with the exact same specifications as the drum brake vehicle borrowed from the US Xpress fleet that was used for the "as-received" testing, it was decided to use this Volvo-owned vehicle as the drum brake tractor for the remainder of the testing. Its braking system was rebuilt with new drums and linings and the tires were replaced with new ones identical to those installed on the disc brake tractor. This vehicle was then burnished in the same fashion as the disc brake tractor.

Figure 6 shows the 60 mph stopping distance results for both the drum brake and disc brake tractors with new burnished components using the Control Trailer. Figure 7 shows the results for the 75 mph stops. Also shown for comparison purposes in both figures are the results for the "as-received" testing.

The data shown in Figure 6 indicate that the drum brake tractor with burnished brakes stopped an average (three stops) 10.7 percent shorter than the "as-received" drum brake tractor. The 75 mph stops (Figure 7) show a 17.6 percent improvement in average stopping distance with new burnished drum brakes.

Looking at the disc brake tractor, the new burnished brakes stopped 13.4 percent shorter at 60 mph and 4.5 percent shorter at 75 mph than the corresponding "as-received" brakes.

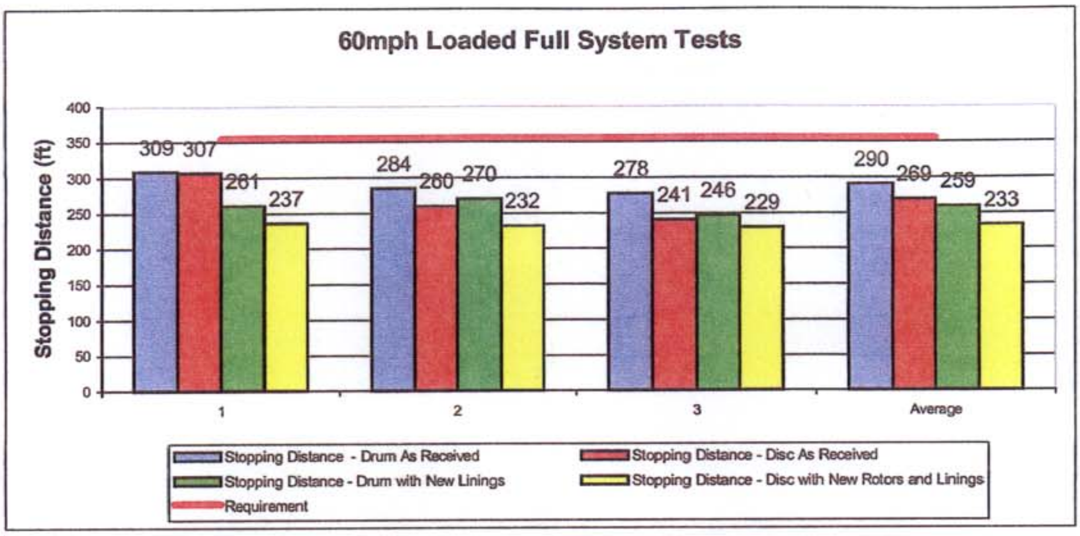


Figure 6 – Summary Results – 60mph Stopping Distance

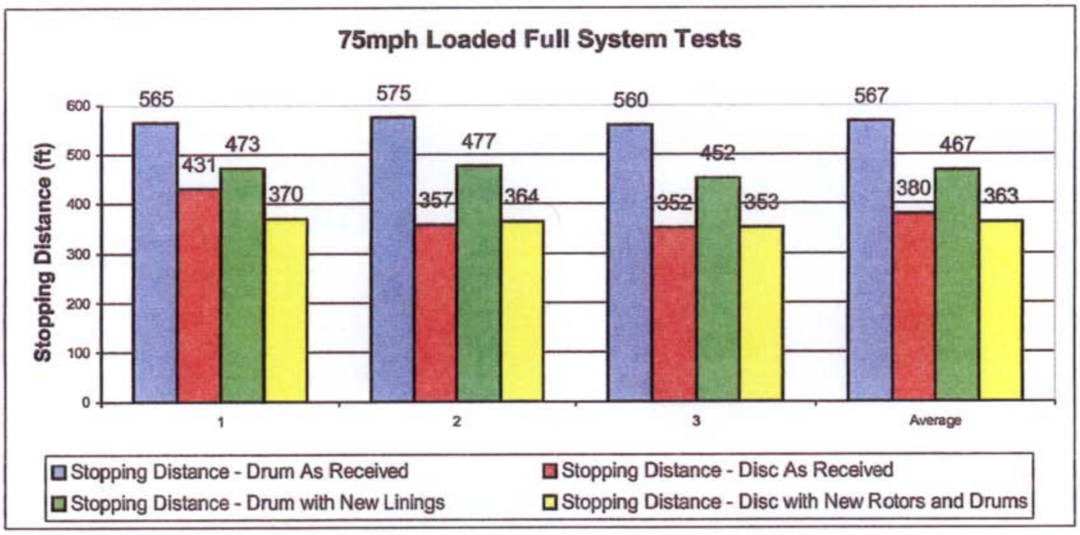


Figure 7 – Summary Results – 75mph Stopping Distance

Comparing the performance of the new, burnished disc brakes to the new burnished drum brakes using the data in Figures 6 and 7 indicates that the average 60 mph stopping distance is 10.0 percent shorter with disc brakes and the average 75 mph stopping distance is 22.3 percent shorter with disc brakes. In the "as-received condition", the disc brake improvements (compared to "as-received" drum brakes) were 7.2 percent and 33.0 percent at the 60 mph and 75 mph test speeds respectively.

Tractor Parking Brake Drawbar Force with New Burnished Brakes

Figure 8 and Figure 9 show the parking brake forces (per axle) measured in the drawbar test for the drum brake and disc brake tractors respectively. The drum brake tractor was only equipped with parking brakes on the forward drive axle (axle no.2). The disc brake tractor had parking brakes on both drive axles (axle nos. 2 and 3). Comparing Figures 8 and 9 indicates that the parking forces per axle with disc brakes are significantly higher (approximately 5,000 lbs or 70 percent) than those with drum brakes. Parking brake chambers on the drum brake tractor were 3030 double-diaphragm type. The disc brake tractor used 2424 chambers with piston-type parking actuators.

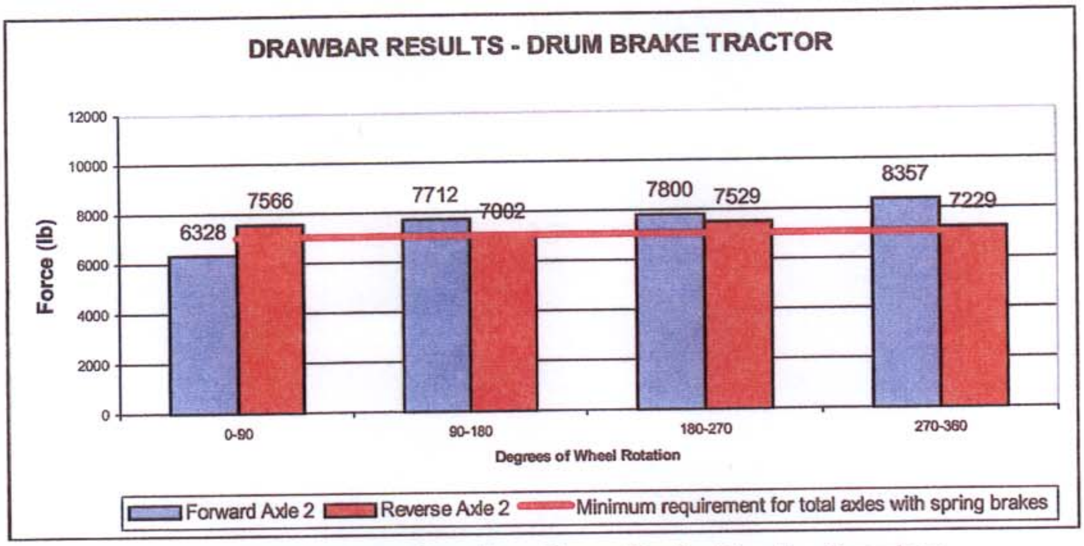


Figure 8 – Summary Results – Drum Brake Tractor Drawbar

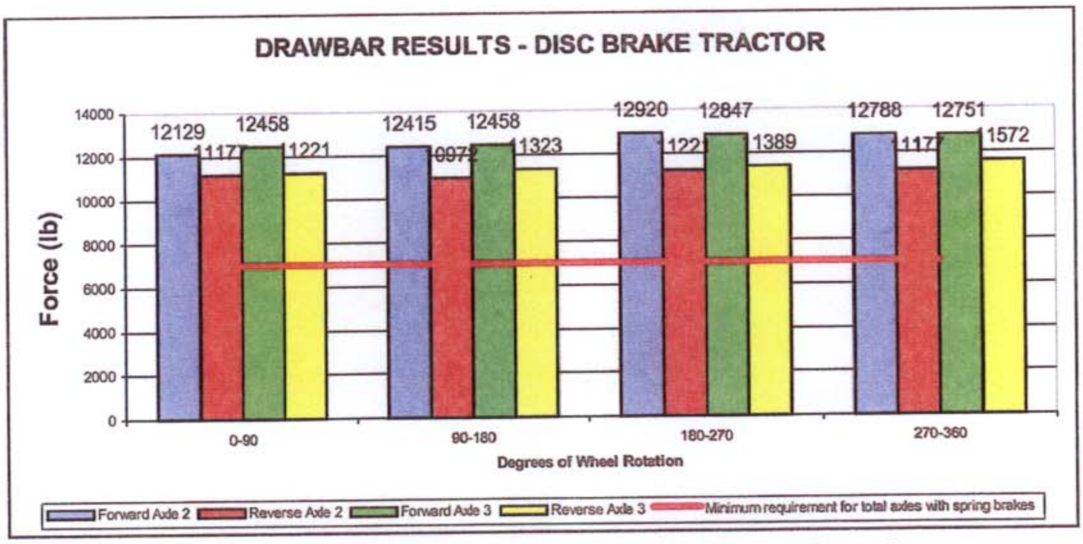


Figure 9 – Summary Results – Disc Brake Tractor Drawbar

Characterization of Trailer Brakes at Low Pressures (New, Burnished Brakes)

A single Great Dane van trailer was used during the trailer-brake-only brake characterization testing. To change the brake system from disc to drum and visa versa the trailer slider assembly was changed. Both sliders were setup with identical pneumatic air valves and ABS systems. The only difference was the foundation brakes. Both trailer sliders were burnished separately using an un-braked tractor to tow the trailer.

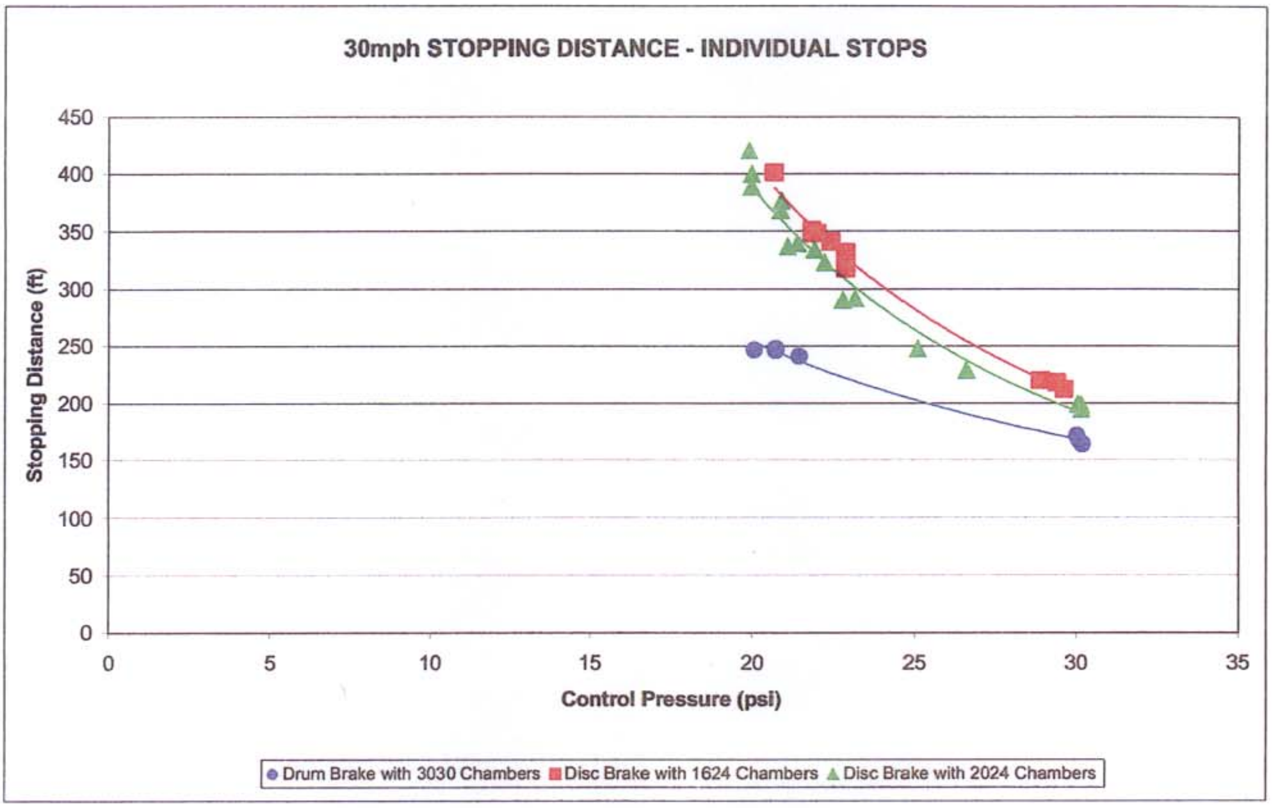
The trailer brakes were characterized by running stops from 30 mph and 60 mph at 20 psi and 30 psi. The purpose of these stops was to evaluate braking forces in typical low-pressure stopping situations. The stops were run with the trailer brakes only using a special system that applied a regulated constant pressure to the trailer's control line. During these tests the total combination weight was 40,000 lbs, which is equal to the trailer tandem's GAWR.

Initially the disc brake slider was tested with Type1624 brake chambers (16 service/24 parking). The disc brakes with this size service chamber did not perform as well as the drum brakes (with 3030 chambers) at the low apply pressures so the service chamber size on the disc brake slider was changed to a Type 20 (using a 2024 brake chamber). The Type 20 service chamber was used through the remainder of the testing. It should be noted that the trailer drum brakes used in this test were 8-5/8 inches wide and are considered to be "heavy-duty" compared to the more common 7-inch wide drum brakes.

The trailer brake characterization stops were made with the drum brakes, the disc brakes with Type 16 service chambers, and the disc brake with Type 20 service chambers. A summary of the stopping distances and average decelerations for the stops at 30 mph and 60 mph are shown in Figures 10 and 11. The three different brake configurations were also run on the low-speed roller brake tester. A plot of total trailer brake force versus control pressure for the three braking arrangements on the roller tester is shown in Figure 12.

Figure 10 indicates that the 20 psi stopping distances from both 30 mph and 60 mph with the drum brakes are significantly shorter than those with the disc brakes indicating that the drum brakes were more effective than the disc brakes at this pressure. At 30 psi, the difference between disc and drum brakes became much smaller. It is interesting to note that the Type 16 and Type 20 chambers produced almost no difference in disc brake output at these low pressures.

The decelerations shown in Figure 11 are essentially the inverse of the stopping distances shown in Figure 10. Again there is little difference between the Type 16 and 20 service chambers on the disc brake and again the drum brake appears to be more effective than the two disc brake configurations, although the difference drops as the pressure increases. Because the disc brake slopes are higher than the drum brake slopes, particularly at 60 mph, it is likely that the discs would become more effective than the drums in higher-pressure stops.



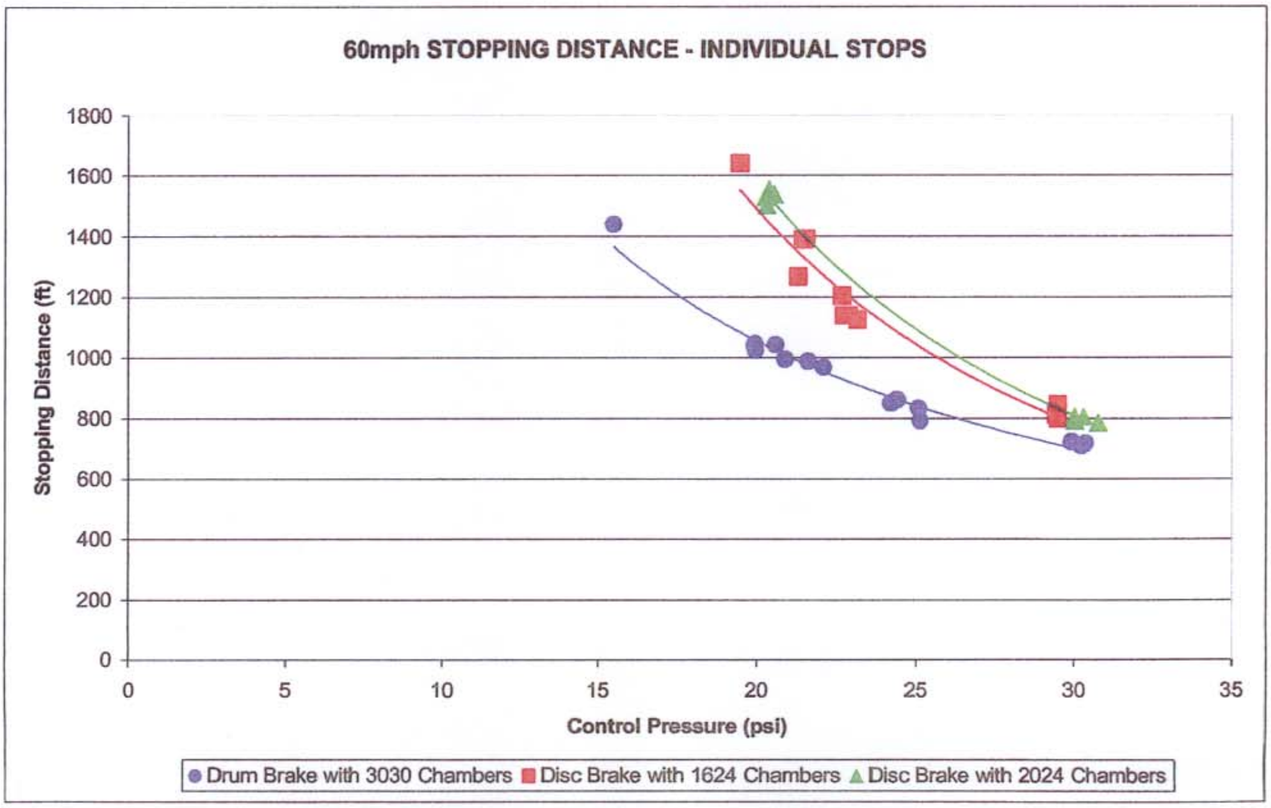
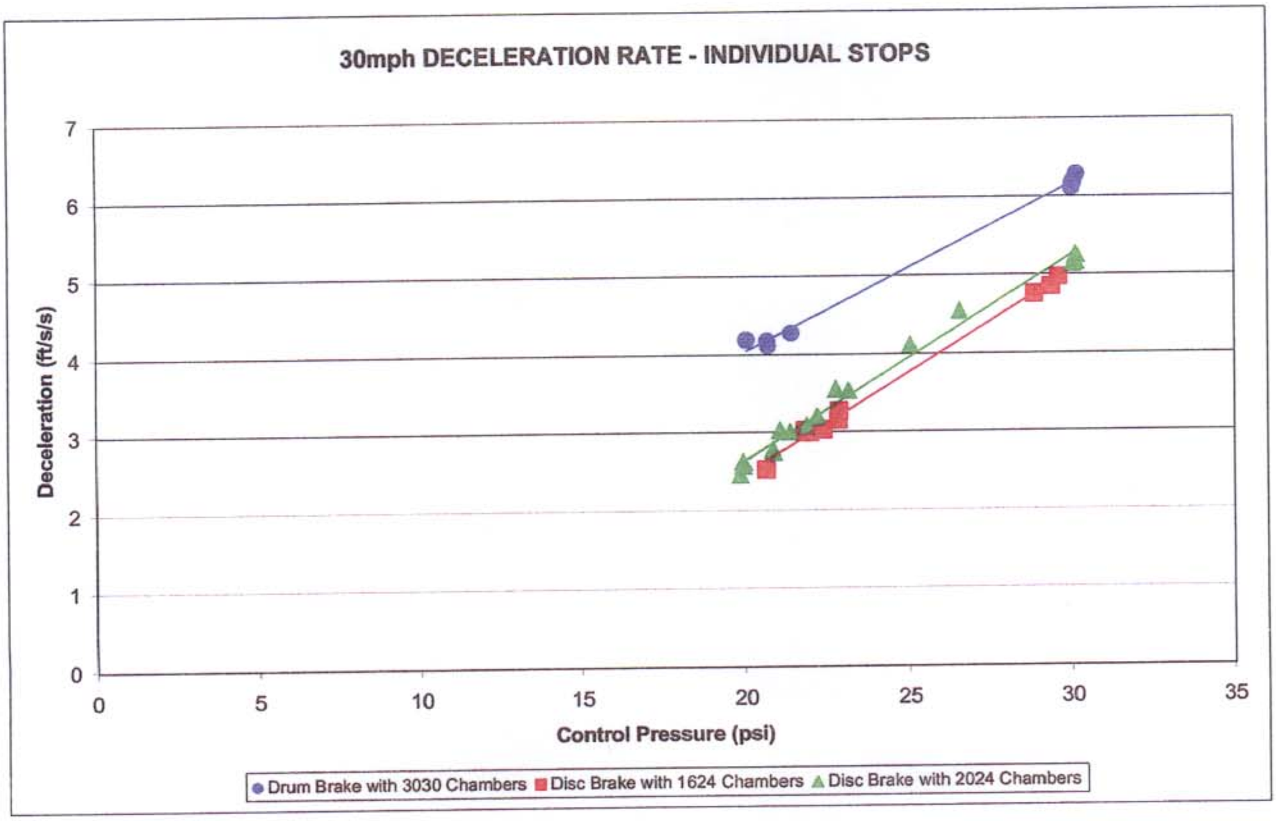


Figure 10 - Summary Results - Trailer Brakes Only Stopping Distance



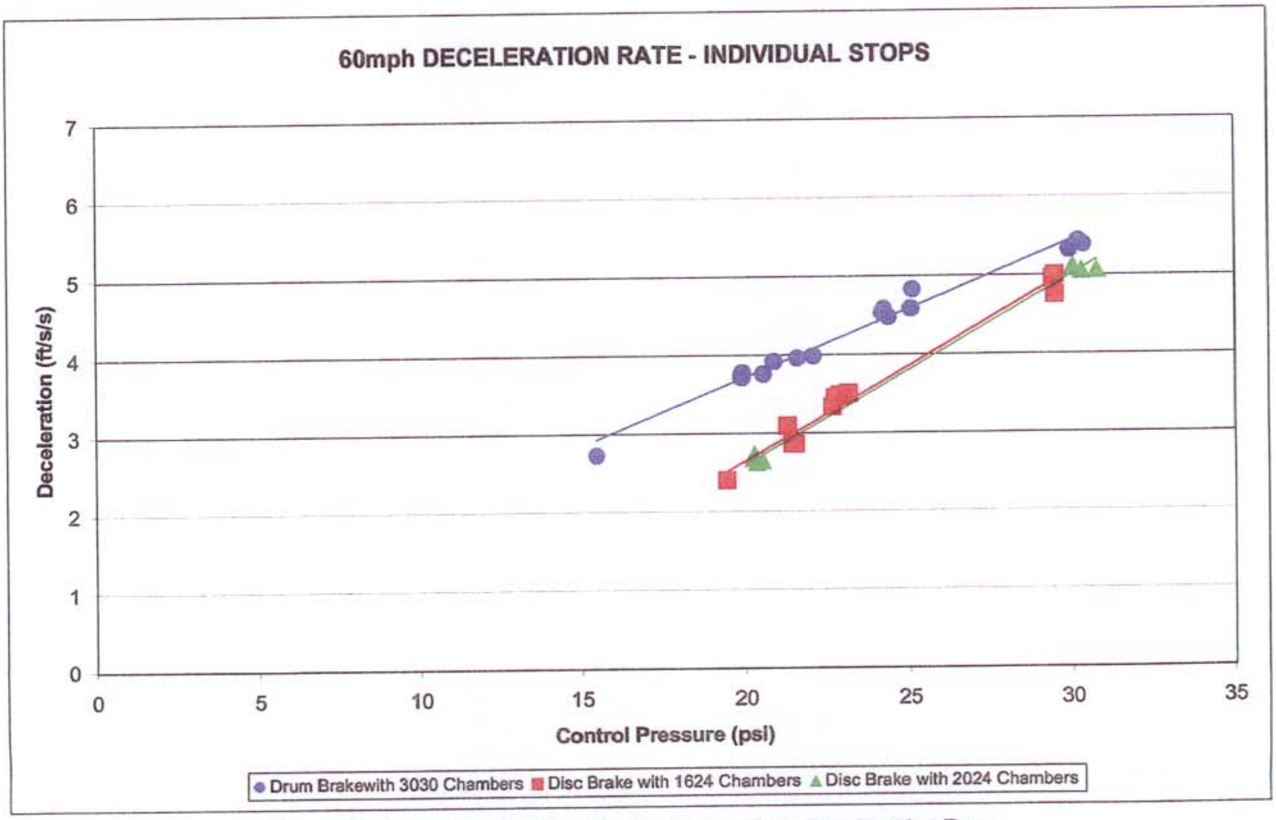


Figure 11 - Summary Results - Trailer Brakes Only Deceleration Rate

Figure 12 provides the roller brake tester results on the three different trailer brake configurations. The graphs, which represent brake force measurements at 1.5 mph, actually give an indication as to why the disc brakes are less effective than the drum brakes at low pressures in the 30 mph and 60 mph tests. While effectiveness can vary with speed making the low speed roller brake measurements somewhat unreliable in predicting high speed performance, the threshold pressure or control line pressure at which braking force starts to occur is not affected by speed. It can be seen in Figure 12 that the disc brake threshold pressures are 3 to 4 psi higher than the drum brake threshold pressures. This is likely due to the difference in the brake chambers used on the brakes. As the chamber size gets smaller, threshold pressure increases. It takes a higher pressure in the smaller chamber in order to achieve the force required to actuate the brake. While this pressure difference seems small, it can have a significant effect in low-pressure stops.

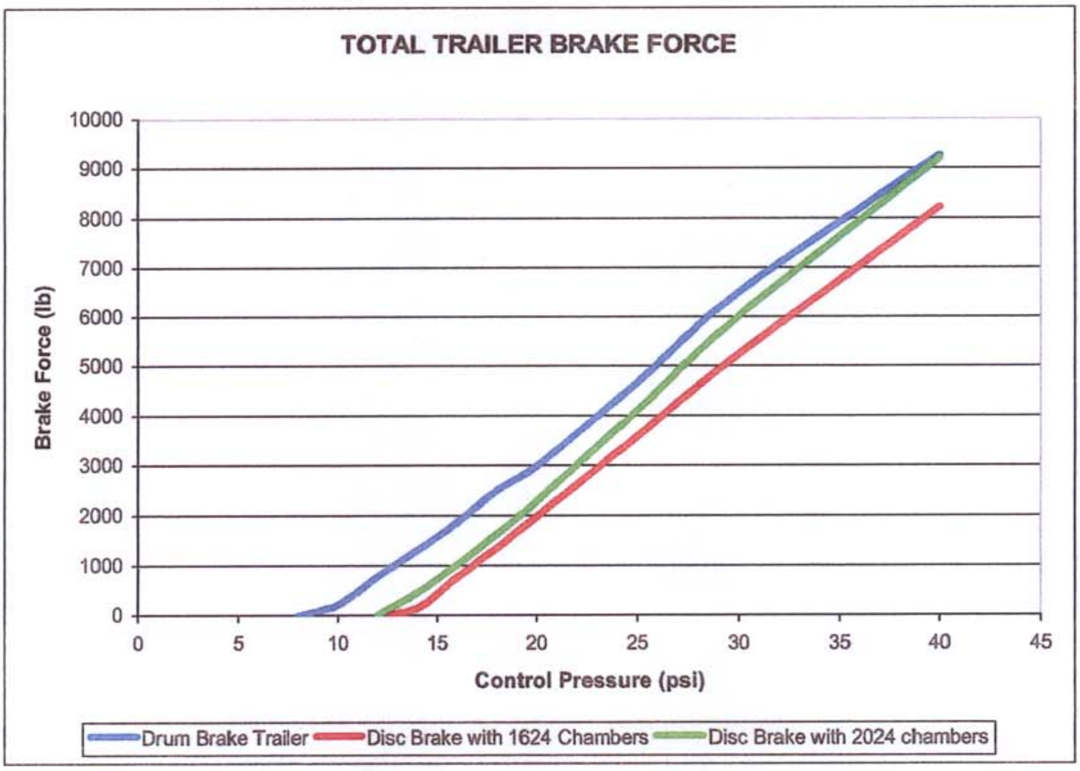


Figure 12 – Summary Results – Total Trailer Brake Force Measured by Roller Brake Tester

Tractor Trailer Combination Stopping Distance Tests

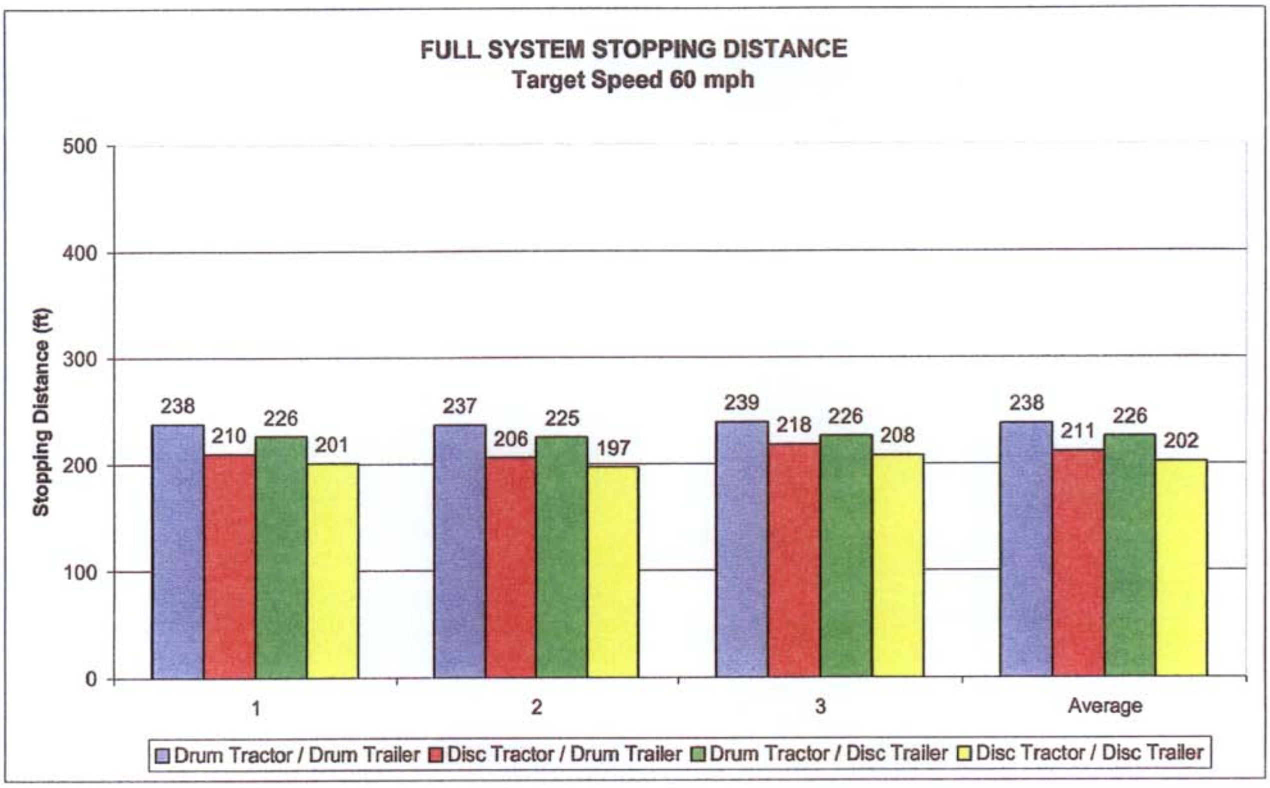
Following the tractor-only and trailer-only braking tests, stopping distance tests were run on the VN tractor / Great Dane trailer combination with the four possible braking system configurations (drum/drum, drum/disc, disc/drum, and disc/disc). These stops were all run at a GCW of 80,000 lb. These combination-vehicle stopping tests were run with fully intact brake systems at 60 mph and 75 mph and then again at 75 mph with various failures introduced. These included failed primary tractor reservoir, failed secondary tractor reservoir and failed trailer control line.

Figure 13 shows the results of the full system stops at 60 mph and 75 mph for the four different braking system configurations. The shortest 60 mph full-system stopping distance was recorded by the disc tractor/disc trailer combination (197 feet - best of three stops and 202 feet - average of three). The longest set of stops was with the drum tractor/drum trailer combination (237 feet - best of three and 238 feet - average of three). This represents a 17.8 percent increase over the all-disc combination. Comparing these results to the stopping distances of the disc and drum brake tractors with the FMVSS 121 Control Trailer (Figure 6) it can be seen that these combination distances are somewhat shorter than those with the Control Trailer (21 feet shorter for the drum braked tractor and 31 feet shorter for the disc brake tractor).

The 75 mph data in Figure 13 indicate similar rankings between the various brake system configurations as did the 60 mph data. The average stopping distance for the all-disc brake configuration was 19.2 percent shorter than that for the all-drum configuration.

Figure 14 shows the results of the three different sets of failed system stops at 75 mph (60 mph tests were not run with system failures) for the four different braking system configurations. It can be seen that the worst-case failure mode was the primary reservoir failure on the all-drum brake configuration (average stopping distance was 1013 feet). In this same failure condition, if either of the units have disc brakes, the stopping distance was considerably shorter (338 to 446 feet shorter depending on the brake configuration).

Another failure mode that produced noticeably poor stopping performance was the failed trailer control line condition with the two combinations where the tractor had drum brakes. In these cases the average stopping distances were 888 feet and 850 feet.



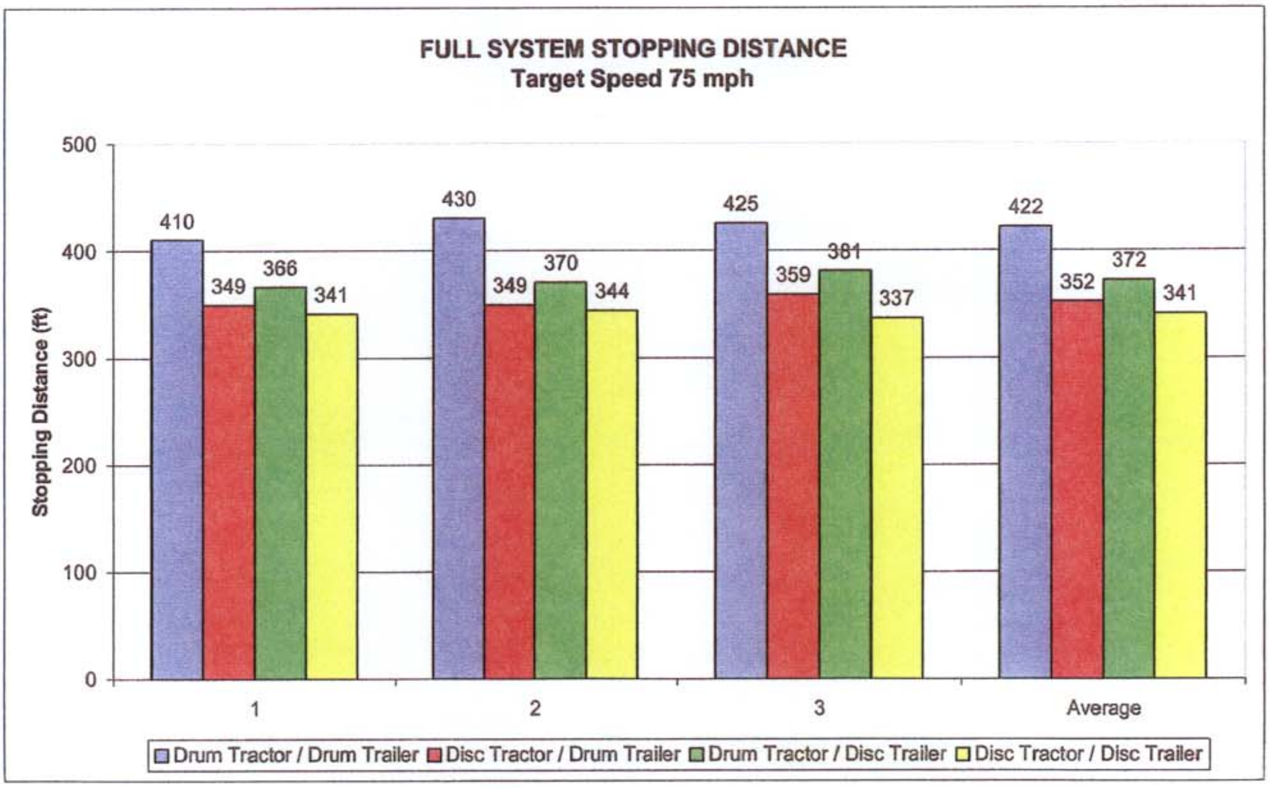


Figure 13 - Summary Results - Combination Vehicle Full System Stops at 80,000 lbs

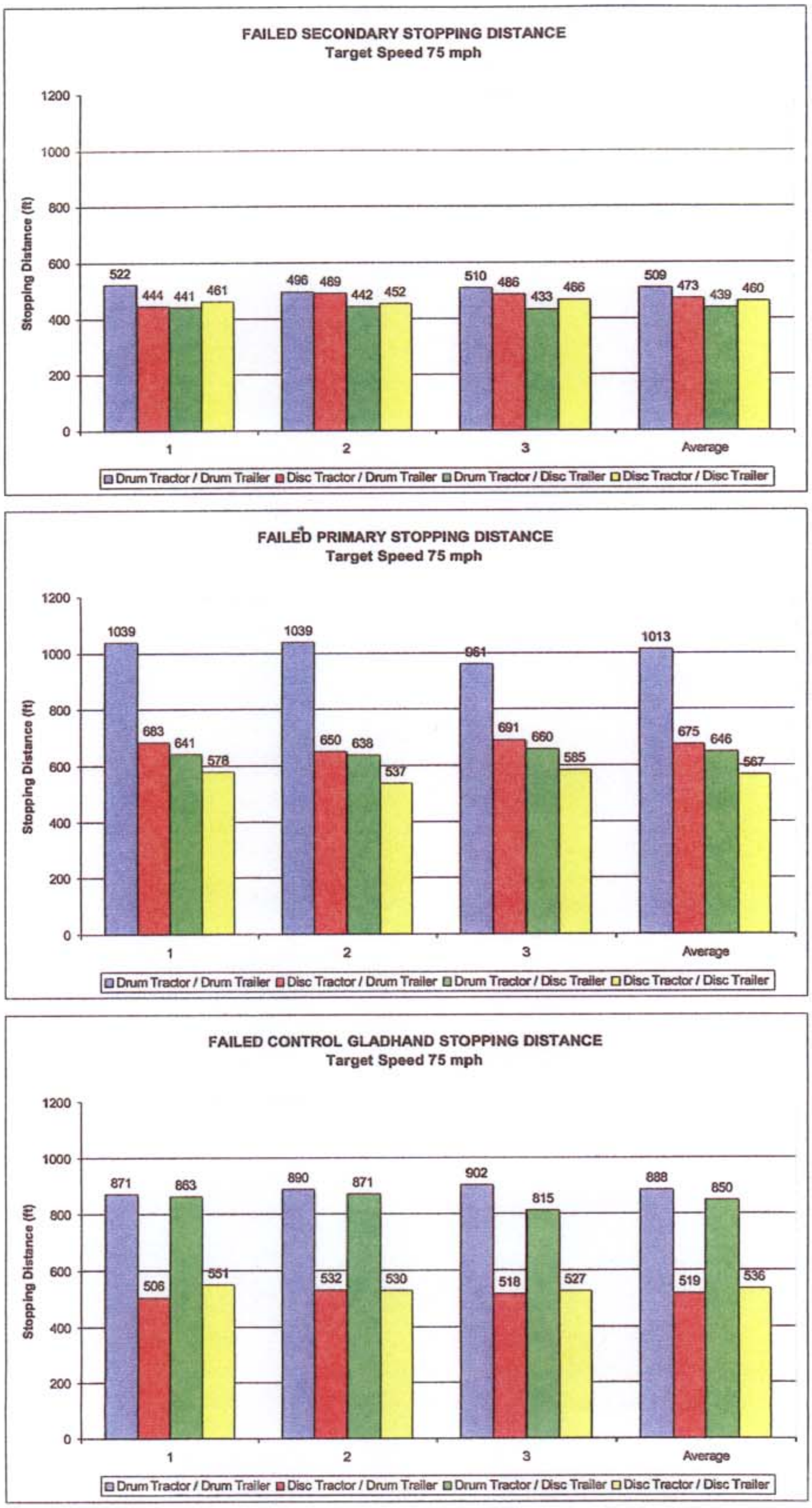


Figure 14 - Summary Results - Combination Vehicle Failed System Stops at 80,000 lbs

Pneumatic Timing

Results of the timing tests for the four tractor- trailer combinations are shown in Figure 15. The data shown represent the average timing of the left and right side brakes on the steer axle and all four brakes on the tractor drive and trailer tandems. All tests were run with the combinations fully loaded and the ECBS power on. Each test was run three times and the data shown are based on the average of these three runs. The top chart of Figure 15 shows the application times (0-60psi) for the four tractor-trailer configurations. It can be seen that the disc brake tractor, which has EBCS, had a faster apply times at the front and rear brakes than the drum brake tractor. The disc trailer was slightly faster on application than the drum trailer when compared with the same tractor attached.

It is interesting to note that the trailer apply times are slightly faster with the drum brake tractor compared to the disc brake tractor, despite the fact that the disc brake tractor has ECBS. Since the trailer does not have ECBS, the trailer brake control is accomplished pneumatically with the ECBS tractor and the trailer timing benefits that could be achieved with an all-ECBS combination cannot be realized.

The bottom chart in Figure 15 shows the brake release times for the tractor-trailer combinations. The chart indicates the steer axle was slower on release with the disc tractor than the drum tractor but the drives were faster on release with the disc tractor. The disc trailer was slightly faster on release than the drum trailer when compared with the same power unit and trailer release times were slightly faster with the drum brake tractor compared to the disc brake tractor.

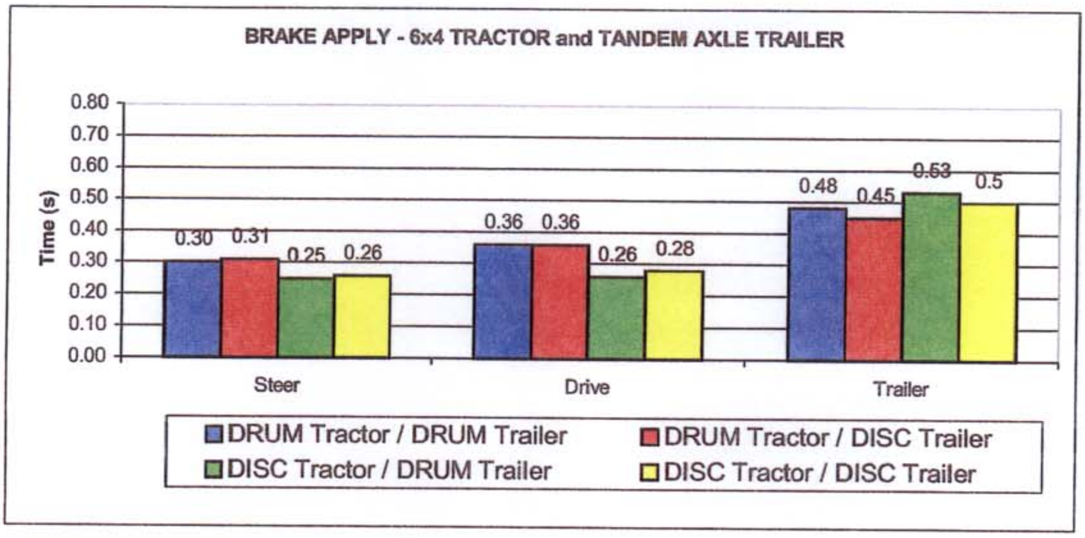
Pneumatic Balance

Results for the tractor-trailer pneumatic balance tests are given in Figure 16. These graphs show the pressure at one front-axle chamber, one drive-axle chamber, and one trailer-axle chamber versus control pressure at the trailer gladhand for four different situations:

- Drum brake tractor combinations (results would not depend upon trailer brake type or trailer loading).
- Disc brake tractor combinations where the trailer was fully loaded (disc or drum brakes on the trailer would give the same results).
- Disc brake tractor combinations where the trailer was loaded at the front-end only (disc or drum brakes on the trailer would give the same results).
- Disc brake tractor combinations where the trailer was fully loaded (disc or drum brakes on the trailer would give the same results).

A loading configuration where the front of the trailer was empty and the rear of the trailer was loaded was not evaluated, as it is not representative of how a van trailer would be loaded in actual service (freight would be added to the front first and removed from the rear first).

The reason that trailer loading impacts pneumatic balance with the disc brake tractor is the load sensing and automatic brake balancing features incorporated into the ECBS system on the disc brake tractor. The ECBS increases steer-axle brake pressure and reduces drive-axle pressure in relation to the trailer control line when the drive-axles of the tractor are unloaded. Since the fully-loaded trailer and the trailer-loaded-at-the-front-only produce the same drive-axle loads, these two conditions result in almost identical brake balance. The ECBS senses load at the tractor drive-axle tandem.



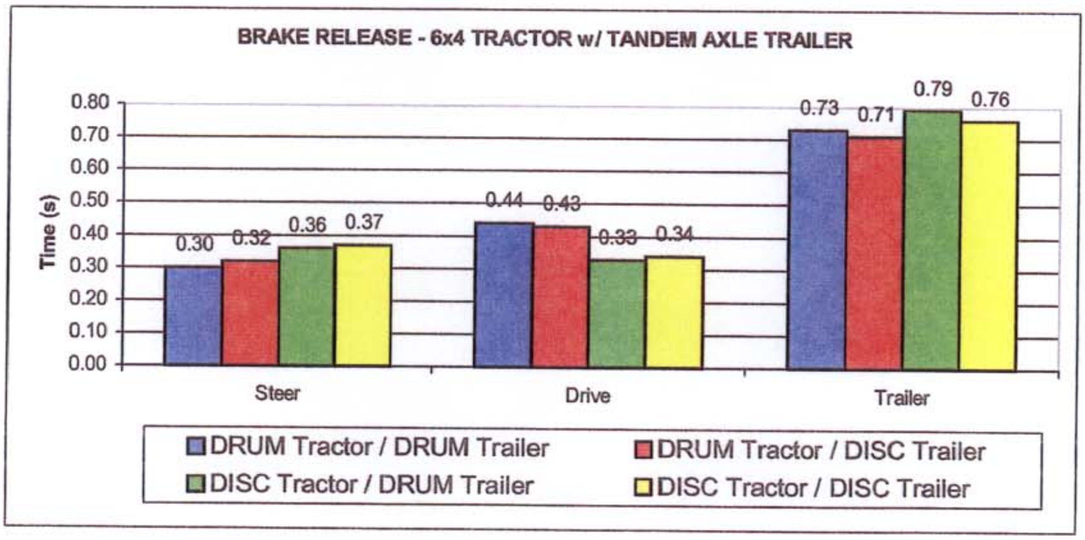


Figure 15 – Summary Results – Timing Test

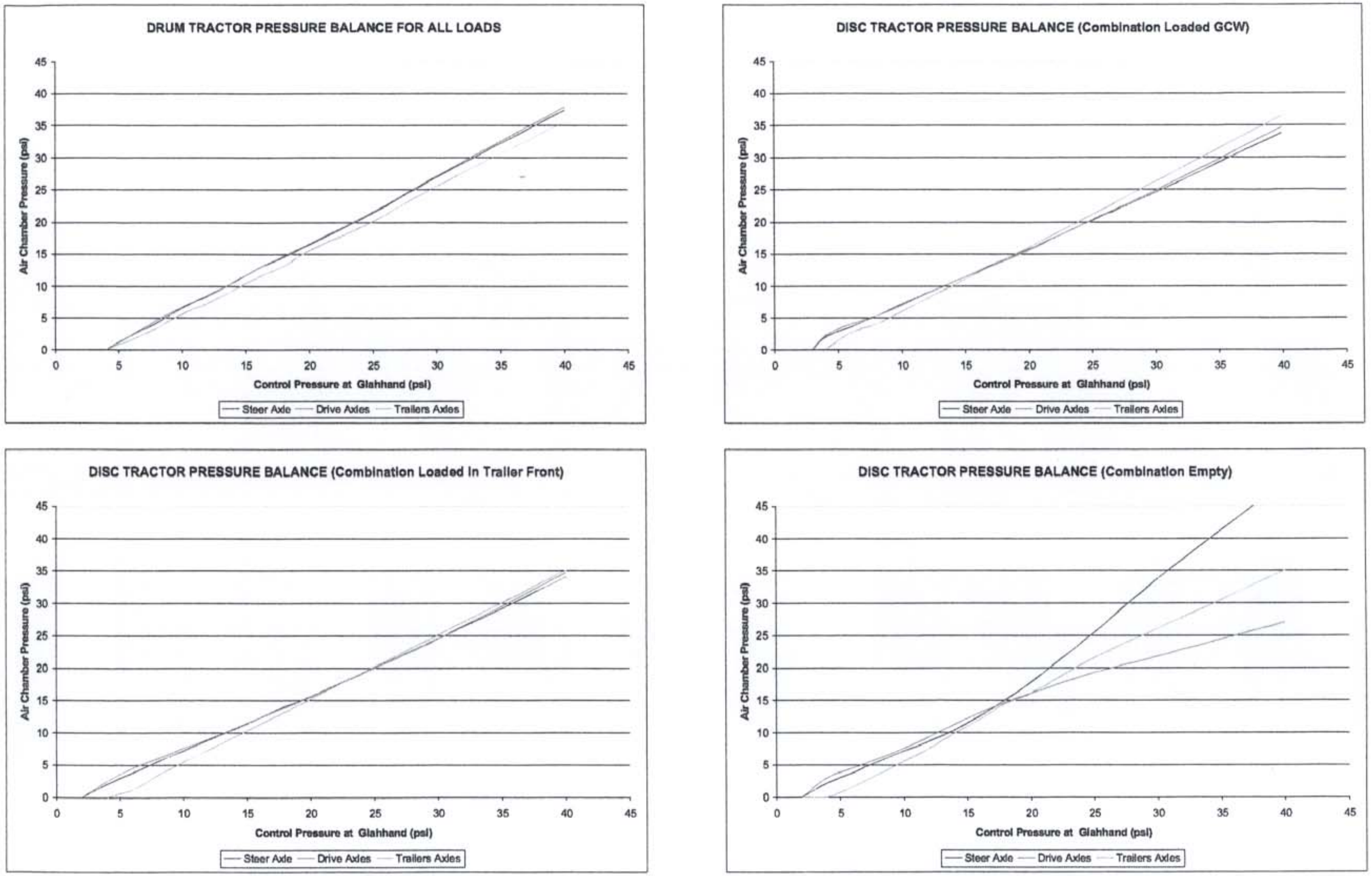


Figure 16 - Pneumatic Balance Results

Brake Force Threshold Pressures

The pressure in the trailer control line when braking starts at each axle group (i.e. the brake force threshold pressure) can have a very significant impact on compatibility. This is because differences in threshold pressures can become significant in brake applications where the brake pressures are relatively low. For example, if the difference in threshold pressure between the tractor tandem and the trailer tandem is 4 psi, and a brake application is made at 10 psi, the axle with the lower threshold pressure will do a lot more of the work. As brake pressures get higher, threshold pressure differences become less significant.

Table 3, derived from the roller brake tester results, shows the nominal brake force threshold pressures for the various axle groups on the test vehicles. Also shown are the "crack" pressures or pressures in the trailer control line when pressure starts to rise above zero in the brake chambers. On the two different trailer brake systems and the drum brake tractor's drive axle, the "crack" pressure shown in Table 3 represents the opening pressure of the relay valve that controls the brakes. This is typically referred to as the valve's "crack" pressure. The crack pressure on the steer axle of the drum tractor as shown in Table 3 is actually the sum of the front-axle quick release valve "crack" pressure and the differential pressure across the primary and secondary circuits of the foot valve. On the ECBS tractor, the "crack" pressure represents the relative pressure differential between the tractor's brake chambers and the trailer control line. The term "crack" pressure does not really apply to ECBS valves as they are electrically controlled.

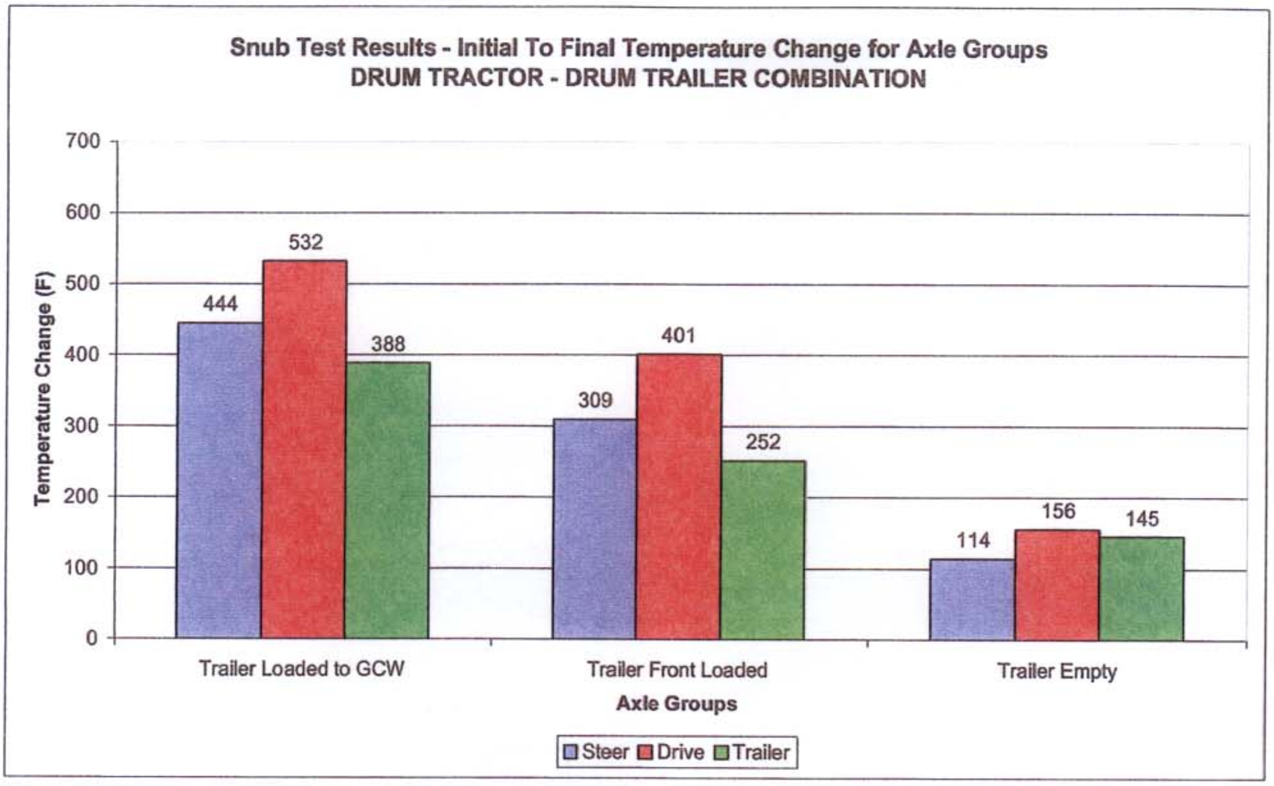
Table 3 – Brake Force Threshold Pressures and "Crack" Pressures

Axle	Threshold, psi		Crack, psi	
Group	**Drum**	**Disc (ECBS)**	**Drum**	**Disc (ECBS)**
Steer	8 - 9	8 – 9	4 – 5	2 - 3
Drive	7 - 8	8 - 9	4 - 5	2 - 3
Trailer	8 - 9	12 - 13	4 - 5	4 - 5

It can be seen in Table 3 that the threshold pressures of all of the axle groups are relatively close together except for the disc brake trailer threshold, which is 3 to 6 psi higher than the thresholds for the other axle groups. Since the trailer "crack" pressure is not higher than that on the other axle groups, the difference lies in the trailer disc brake assembly and not the pneumatic valving.

Snub and Drag Tests

Tractor-trailer combinations with each of the four possible brake system configurations were subjected to snub tests and drag tests at three different trailer loads in order to evaluate temperature balance and compatibility between the various axle groups. One snub test and one drag test were run for each load condition on each combination. Figures 17 through 20 (one figure for each brake system configuration) show the results. In each figure, the graph at the top of the page is for the snub test and the graph at the bottom is for the drag test.



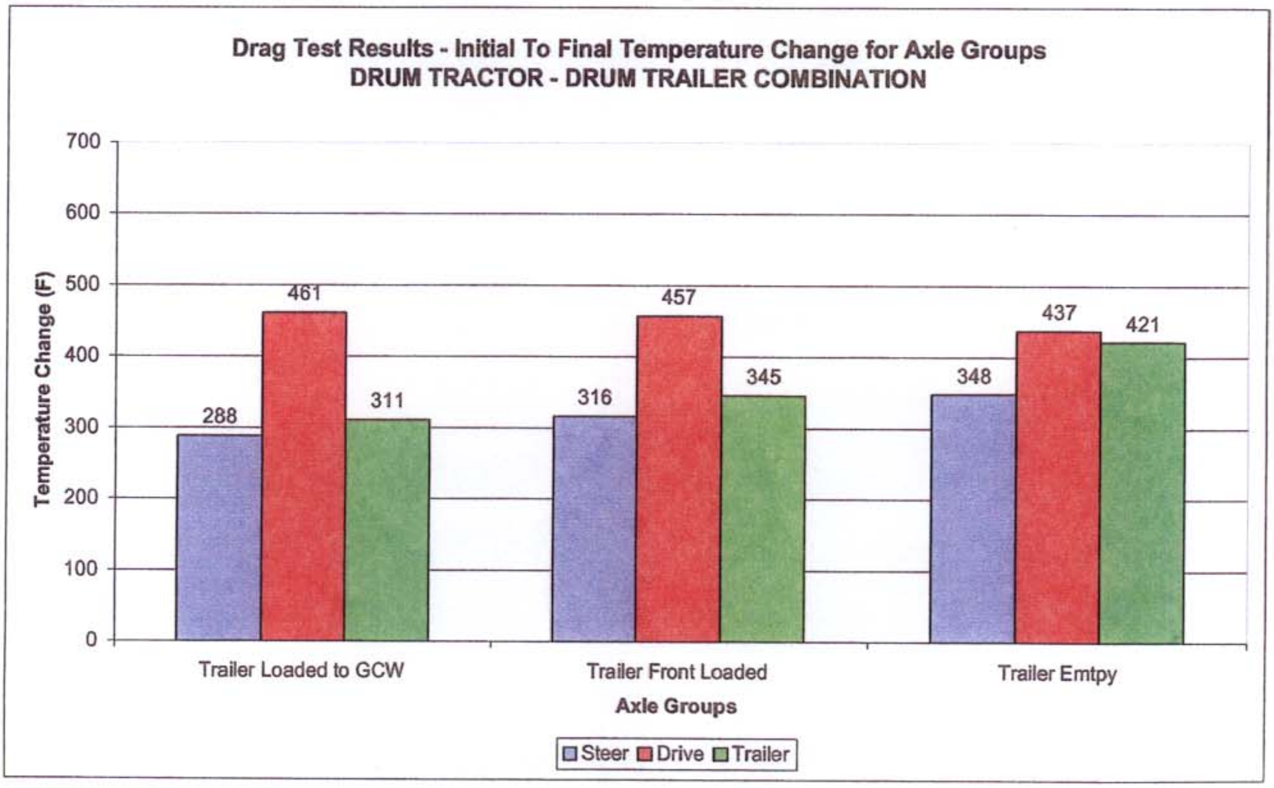
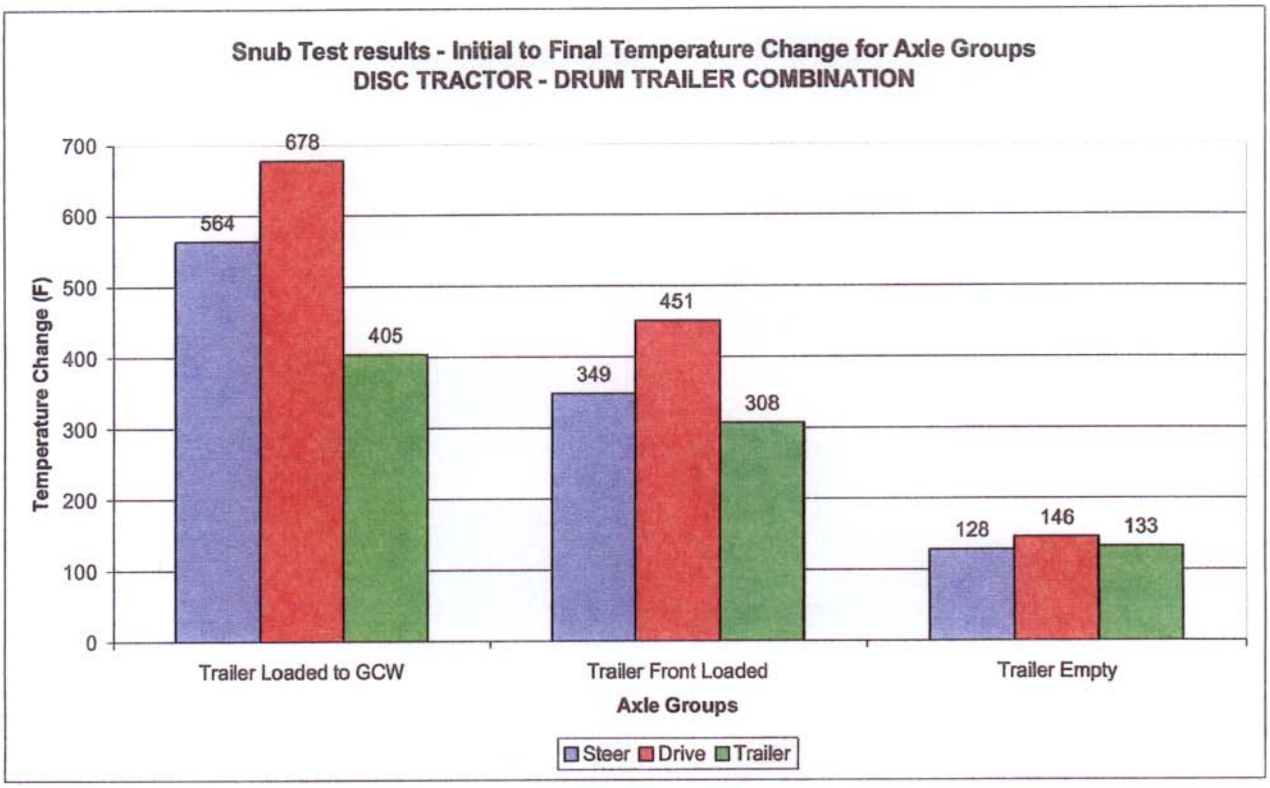


Figure 17 - Snub and Drag Results - Drum Tractor / Drum Trailer



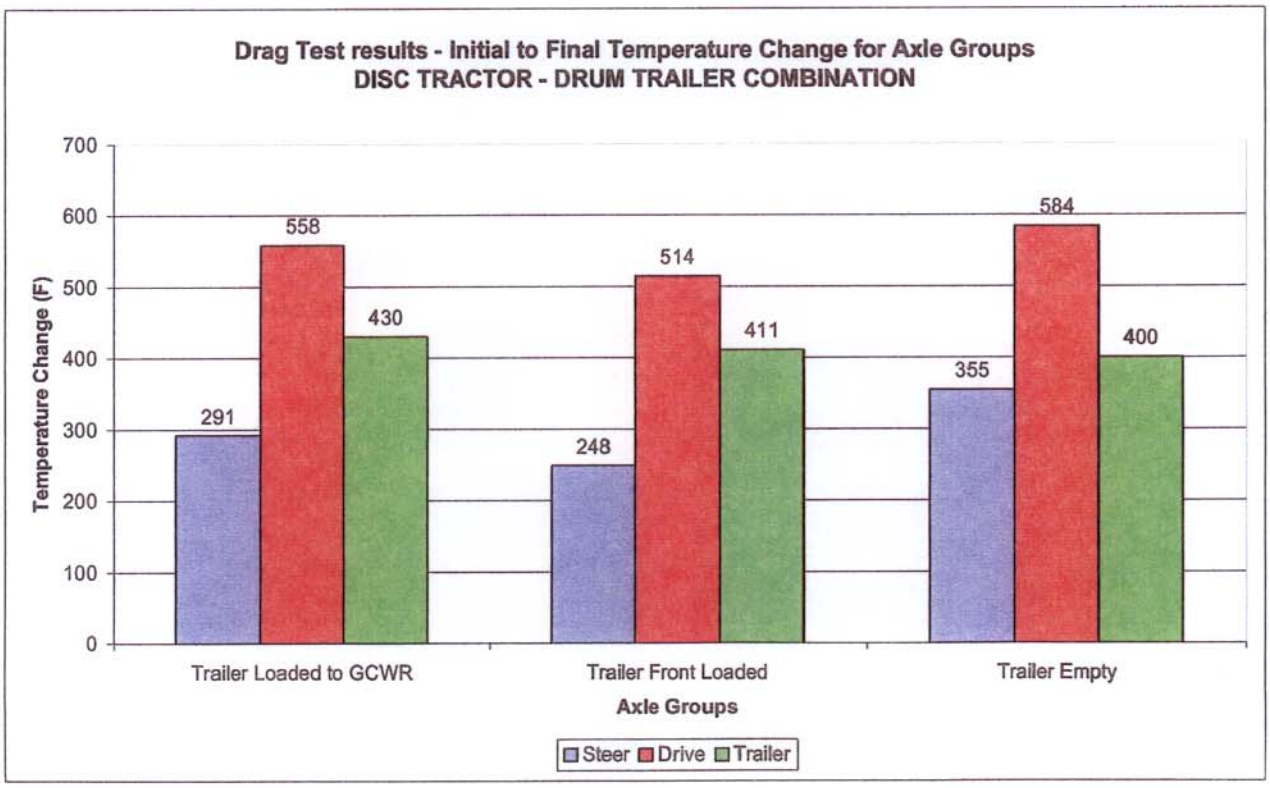
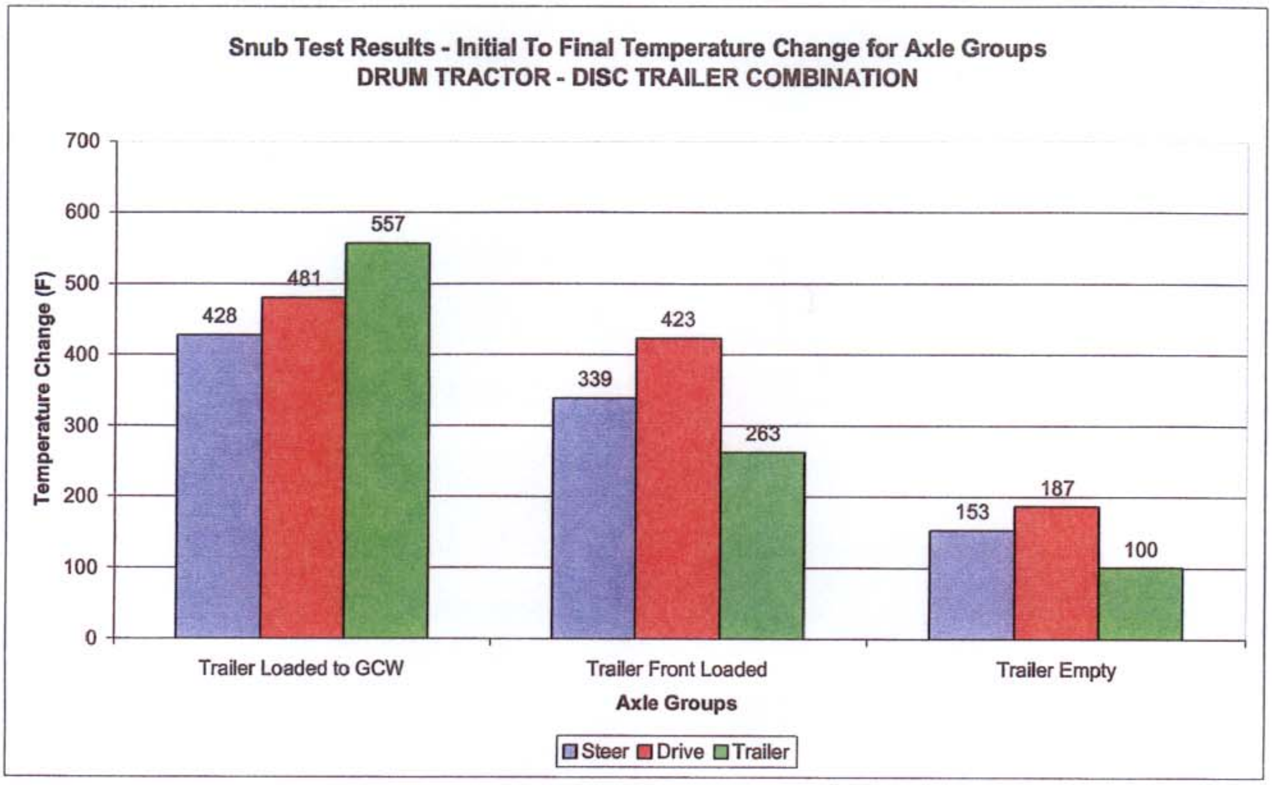


Figure 18 - Snub and Drag Test Results - Disc Tractor / Drum Trailer



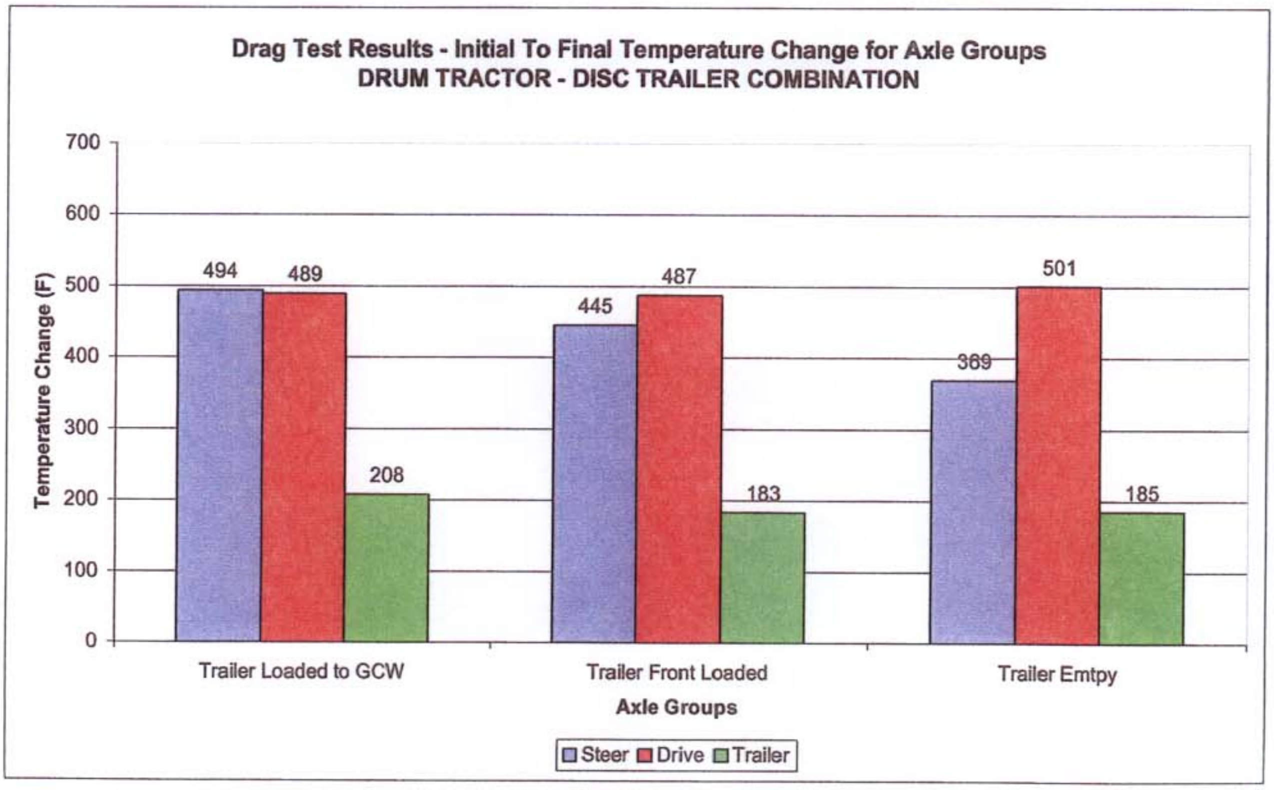
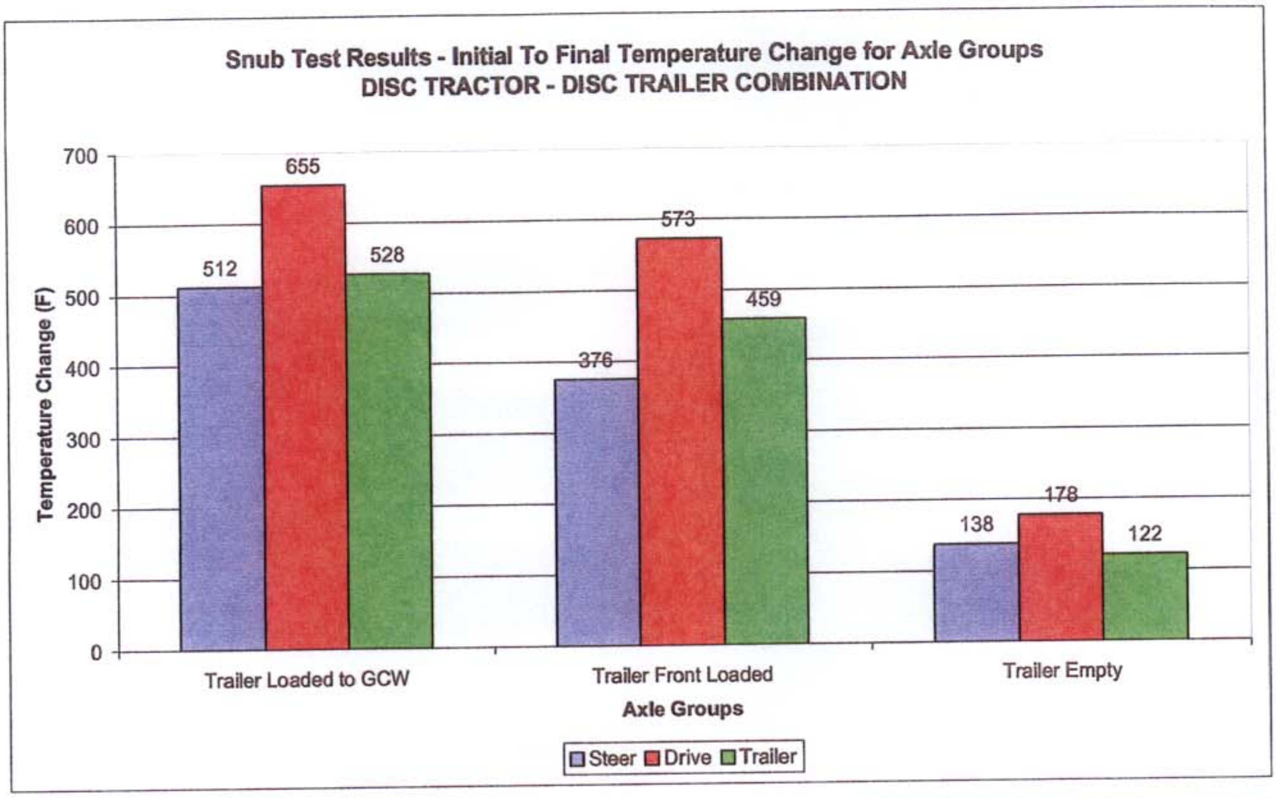


Figure 19 - Snub and Drag Results - Drum Tractor / Disc Trailer



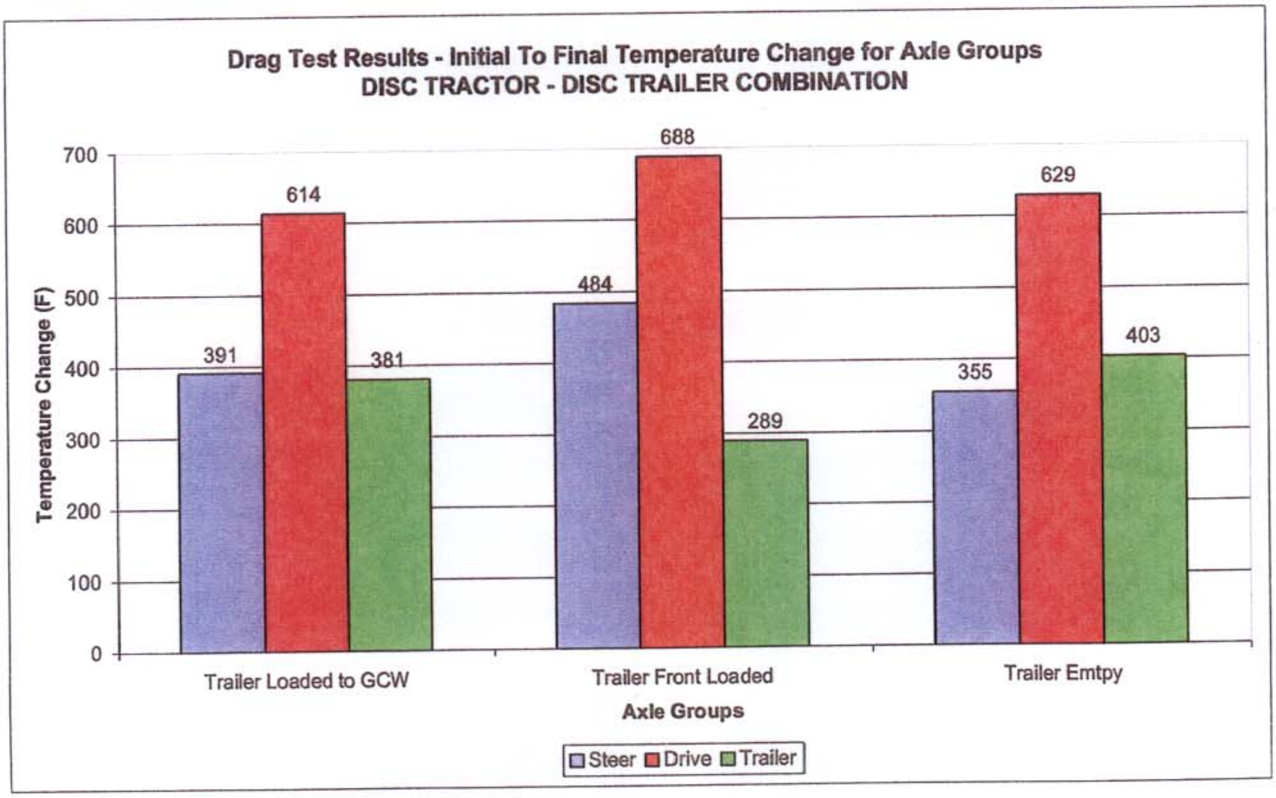


Figure 20 - Snub and Drag Test Results - Disc Tractor / Disc Trailer

On these graphs, each bar represents the average brake temperature increase (average initial temperature minus average final temperature) for a given axle group. Tests were always started when the initial brake temperatures were between 150 and 200°F.

When the snub tests were run at the three different loads the average brake temperature rises were low (100 to 187°F) when the trailer was empty, moderate (252 to 573°F) when the trailer was only loaded at the front-end and higher (388 to 678°F) when the trailer was fully loaded to 80,000 lbs GCW. These differences are due to the fact that the total number of snubs run was constant so that the total energy going into the brakes during the test increased as the load increased. More energy was dissapated per stop as the load was increased.

The situation was different in the drag tests. In this case the test was designed to input the same amount of energy to the brakes regardless of load. This was achieved by forcing the brake system to develop a fixed output (3000 lb drawbar force) over a fixed distance (5 miles) at a fixed speed (30 mph) regardless of load. The primary reason this was done was to investigate the changes in balance that occurred due to the load sensing function of the ECBS as opposed to evaluating a specific grade descent at different loads.

In theory, all three drag tests at the different loads for the same brake configuration should have produced the same overall average brake temperature rises. This was generally the case. For a given brake system configuration the overall vehicle average temperature rise during the drag tests were within 50°F of one another

Generally, for a given brake design the closer the temperature rise between axle groups, the better the compatibility and balance. Since disc brakes run somewhat hotter than drum brakes in a given duty cycle, higher temperatures would be expected with disc brakes compared to drum brakes in a "mixed" combination that was compatible. On the other hand, if the drum brakes were running hotter than the disc brakes in such a mixed combination, this would indicate that the drum brakes were doing too much work.

Table 4 illustrates the fact that disc brakes run hotter than drum brakes for the same "duty cycle". Using data from Figures 17 and 20, Table 4 shows the overall vehicle average brake temperature for the drum/drum combination compared to the disc/disc combination. The overall vehicle averages shown are based on a weighted average where the steer axle is only given half of the weight of the drive and trailer axle (there are only two brakes on the steer axle compared to four on the drive and trailer tandems).

Table 4 – Overall Average Vehicle Brake Temperature Rise (°F)

Test Condition	Drum/Drum Combination	Disc/Disc Combination
Drag tests (average of three tests)	388	484
Snub test at full trailer load	457	576
Snub test at partial trailer load	323	488
Snub test at empty trailer load	143	148

Figure 17, the drum/drum combination, provides somewhat of a baseline as it is the most common configuration today. It can be seen in this figure that the tractor drive-axle ran the hottest in all cases. The lower temperatures in the trailer brakes are due in part to the fact that the trailer drum brakes are 8-5/8 inches wide compared to the more common 7 inch width on the drive axle. It is fairly typical that the front brakes would run cooler than the drive-axle brakes in such a combination and this was the case here.

Figure 18 shows the disc/drum combination. This would be the typical mixed combination in the US Xpress fleet. Here the tractor disc brakes were running hotter than the tractor drum brakes in the all-drum configuration, which is expected. What is not quite expected is the fact that the trailer drum brakes are running slightly hotter than they did in the all-drum configuration indicating that the disc tractor is not doing quite as much work as the drum tractor. Part of this could be due to the slightly higher threshold pressure on the drive axle brakes on the disc tractor.

Figure 19 shows the drum/disc combination. Compared to the drum/drum combination the drum tractor here was running hotter in the drag tests and in the snub tests with the partial-load and empty-trailer conditions. The disc brake trailer was running very cool in the drag tests and the empty-trailer snub tests. In the fully-loaded snub tests the balance changed dramatically and much more work shifted to the trailer. The disc trailer ran much hotter than the drum tractor and the drum tractor ran cooler than it did in the same test condition with the drum/drum configuration.

This change in balance can actually be explained by the higher brake force threshold pressure on the disc trailer. The trailer characterization data indicated that at low pressures, the disc brake trailer was much less effective than the drum trailer due to the higher brake force threshold pressure. As brake pressures increased to about 30 psi the disc trailer effectiveness approached that of the drum trailer. In the snub tests at full load the brake pressure was approximately 30 psi. In the snub test with the empty trailer and in the drag tests, the pressure was much lower and very close to the disc brake trailer's brake force threshold.

Figure 20 shows the disc/disc combination. There was very poor temperature balance between the tractor drive brake temperature and the trailer brake temperature in the drag tests but the situation improved in the higher-pressure snub tests. This problem is again due to the high threshold pressure of the trailer disc brakes. The fact that the trailer runs hotter in the drag tests with the disc/disc combination than it did with the drum/ disc combination is a further indication that the threshold pressure of the disc tractor is slightly higher that that of the drum tractor.

SUMMARY AND CONCLUSIONS

"As –Received" Stopping Distance Performance

- The stopping distances of both the disc brake and the drum brake Volvo VN 6x4 tractors that had been in use in the US Xpress fleet for over 300,000 miles easily met the requirements of FMVSS 121.

- Using an un-braked FMVSS 121 Control Trailer to load the as-received tractors to GVWR, the average stopping distance (three stops) of the disc brake tractor, which was also equipped with ECBS, was approximately 7 percent shorter at 60 mph and 33 percent shorter at 75 mph compared to the drum brake tractor.

- The first test stop, conducted at 60 mph, on both the as-received drum brake and disc brake tractors (after warming the brakes) produced virtually identical stopping distances (309 feet drum vs. 307 feet disc), however, the disc brake tractor's performance improved to a greater degree by the third 60 mph stop (241 feet disc vs. 270 feet drum). Without additional testing, it is not clear if this similar performance between the disc and drum brakes on the first stop would be representative of the other vehicles in the US Xpress fleet. It is also not clear if the similar "first-stop" distances would have occurred had the 75 mph stops been run before the 60 mph stops.

Rebuilt and Burnished Stopping Distance Performance

- After rebuilding and burnishing the drum brake and disc brake tractors, stopping performance with the FMVSS 121 control trailer improved. The drum brake distances improved 11 percent at 60 mph and 18 percent at 75 mph. The disc brake distances improved 13 percent at 60 mph and 4 percent at 75 mph.

- Stopping distances of the disc brake tractor with new, burnished brakes (using the Control Trailer) were shorter than those with the drum brake tractor with new burnished brakes by 10 percent at 60 mph and 22 percent at 75 mph.

- Stopping performance of the VN tractor/Great Dane semi-trailer combinations loaded to 80,000 lbs at 60 and 75 mph was the best when disc brakes were on both units of the combination. The all-disc combination stopped 15 percent shorter at 60 mph and 19 percent shorter at 75 mph than the all-drum brake combination. Both of the mixed combinations (disc/drum and drum/disc) performed better than the all-drum combination and the percentage improvement was greater at 75 mph.

- Equipping one of the units in the combination with disc brakes generally resulted in a significant improvement in failed-system performance (assuming some of the disc brake axles remained operational). The worst-case failure evaluated was one where the tractor and trailer were equipped with drum brakes and the primary reservoir was failed. In this case where only the steer-axle and trailer-tandem brakes were operational, 75 mph stopping distance was over 1000 feet. With this same failure if only the trailer was equipped with disc brakes, this distance was reduced to 650 feet. In those cases where the trailer control line was failed (no trailer brakes), the combinations with the disc brake tractor stopped almost 40 percent shorter than those with the drum brake tractor.

Parking Brake Performance (Rebuilt, Burnished Brakes)

- Parking brake forces, on a per-axle basis, were approximately 70 percent higher on the disc brake tractor based on tests with new, burnished brake components.

Trailer Brake Characterization at Low Pressures (Rebuilt, Burnished Brakes)

- At low brake control line pressures (20 to 30 psi), brake forces on the Great Dane semi-trailer with the disc brake slider were significantly lower than those achieved with the drum brake slider, primarily due to the relatively high brake force threshold pressures for the disc brakes. The disc brake slider required 12 to 13 psi in the control line to initiate braking versus only 8 to 9 psi for the drum brakes. At higher control pressures, the disc brake slider developed braking forces that were higher than those on the drum brake slider as evidenced by the shorter combination vehicle stopping distances achieved when the disc brake slider was utilized. The "cross-over" control line pressure at which the disc brake forces began to increase above the drum brake forces appeared to be about 50 psi.

Tractor and Trailer Brake System Compatibility (Rebuilt, Burnished Brakes)

- Brake force threshold pressures have a major impact on compatibility at low brake pressures such as those typical of many on-highway braking situations. The vehicles tested here, with the exception of the disc brake trailer, had relatively similar brake force threshold pressures in the 7 to 9 psi range. The disc braked trailer threshold pressure of 12 to 13 psi was different enough that it prevented the trailer disc brakes from carrying their fair share of the braking load in those situations where brake control line pressures were low (less than about 30 psi).

- The automatic brake proportioning function of the ECBS on the disc brake tractor did not appear to have much impact (positive or negative) on temperature balance, primarily due to the fact that significant pressure balance changes did not occur until the control line pressure was above the range used in "normal" brake applications. The system's primary function is to improve brake force distribution and reduce the possibility of premature ABS cycling in moderate to heavy braking situations.

- At low brake pressures, the disc brake tractor appeared to be producing slightly less braking force than the drum braked tractor as evidenced by slightly higher trailer brake temperature (disc or drum) when the disc brake tractor was connected to the trailer. Shifting more work to the trailer did not appear to be a problem, however, as the trailer brake (disc or drum) temperatures were generally lower when compared to those on the drive-axle brakes.

- Steer-axle brakes always ran cooler than drive axle brakes on both the drum brake and disc brake tractors.